

# The warm-hot gaseous halo of the Milky Way

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## ABSTRACT

The circumgalactic region of the Milky Way contains a large amount of gaseous mass in the warm-hot phase. The presence of this warm-hot halo observed through  $z = 0$  X-ray absorption lines is generally agreed upon, but its density, path-length, and mass is a matter of debate. Here I discuss in detail why different investigations led to different results. The presence of an extended (over 100 kpc) and massive (over  $10^{10} M_{\odot}$ ) warm-hot gaseous halo is supported by observations of other galaxies as well. I briefly discuss the assumption of constant density and end with outlining future prospects.

### 1. Observational evidence for the warm-hot halo

The warm-hot gas, by definition, is the gas in the temperature range of  $10^5$ – $10^7$ K. At these temperatures, most of the elements are heavily ionized and the dominant ionization states of abundant elements are Hydrogen-like or Helium-like. The first report of the presence of such a gas in the circumgalactic region (CGM) of the Milky Way (MW) came with the observation of  $z = 0$  O VII absorption lines in the sightline toward PKS 2155 – 304 (Nicastro et al. 2002). Since then  $z = 0$  absorption lines in X-ray are found along several extragalactic sightlines with one or more of O VII, O VIII, Ne IX, Ne X, C V or C VI lines (Fang et al. 2003; Rasmussen et al. 2003; McKernan et al. 2004; Williams et al. 2005, 2006). High-resolution grating spectra on both *Chandra* and *XMM-Newton* facilitated the detection of these lines, but their spectral resolution is not large enough to separate the location of the absorbing gas into the Galactic thick disk, the CGM and/or the larger-scale local group (LG) medium and most likely all these components contribute to the observed column density (Mathur et al. 2008). All the observations, however, clearly establish that **the CGM of the Milky Way contains warm-hot gas**; this result is agreed upon by most of the authors. The discrepancy is on the extent of the warm-hot gas and its mass content.

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## 2. Covering fraction of the warm-hot CGM

Several papers cited above discussed a single sightline in detail. In order to determine the covering fraction of the warm-hot CGM, observations of several sightlines along many different directions through the Galactic halo are necessary and archival *Chandra* and *XMM-Newton* data are useful for this purpose. Fang et al. (2006) performed a *Chandra* and *XMM-Newton* survey along 20 sightlines and detected  $z = 0$  O VII absorption in 40% of them. Bregman et al (2007) studied 26 sightlines observed with *XMM-Newton*. Gupta et al. (2012) studied 29 sightlines with good S/N (with O VII equivalent width (EW) limit of about 4mÅ) and detected O VII  $z = 0$  absorption in 21, with resulting covering fraction of 72%.

## 3. From equivalent width to column density

All the studies discussed above are with absorption lines in which the observable is the line EW. This needs to be converted to the physical parameter of column density in order to determine the mass of the CGM. For optically thin gas the ionic column density depends simply on the observed equivalent width:  $N(\text{ion}) = 1.3 \times 10^{20} \left( \frac{\text{EW}}{f\lambda^2} \right)$ , where  $N(\text{ion})$  is the ionic column density ( $\text{cm}^{-2}$ ), EW is in Å,  $f$  is the oscillator strength of the transition, and  $\lambda$  is in Å. However, at the measured column densities of N(O VII), saturation could be an important issue as suggested by simulations (Chen et al. 2003) and observational studies of Mrk421 (Williams et al. 2005). Therefore to correctly convert the measured equivalent widths to ionic column densities, we require knowledge of the Doppler parameter  $b$ ; at a fixed EW, column density decreases with increasing  $b$ . The low velocity resolution of *Chandra* gratings makes it unfeasible to directly measure the O VII line width. If multiple absorption lines from the same ion are detected, the relative equivalent widths of these lines can instead be used to place limits on the column density N(O VII) and the Doppler parameter  $b$  of the medium.

Gupta et al. (2012) used this technique with O VII K $\alpha$  and K $\beta$  lines. For O VII, the expected  $\frac{\text{EW}(K\beta)}{\text{EW}(K\alpha)}$  ratio is  $\frac{f(K\beta) \times \lambda^2(K\beta)}{f(K\alpha) \times \lambda^2(K\alpha)} = 0.156$ . Their observations indicated that most O VII K $\alpha$  lines are saturated, so the inferred column densities were larger than those in optically thin case (their Table 2).

Note that the **observed EW values reported by different groups are consistent within errors. The inferred column densities, however, are different based on considerations for saturation.** Bregman et al. (2007) tried to use the same technique noted above to investigate line saturation. They missed the factor of  $\frac{\lambda^2(K\beta)}{\lambda^2(K\alpha)}$  in the equation

above, so for the expected optically thin O VII K $\beta$  to K $\alpha$  EW ratio they used 0.21 instead of the correct value 0.156. This lead them to conclude that the lines are unsaturated, and so underestimate the column density and the mass of the CGM. The saturation effect contributes about a factor of four to the measured column density. The errors on O VII  $\frac{EW(K\beta)}{EW(K\alpha)}$  ratios, however, are large and saturation is not necessarily present in every sightline, but taking this into account makes a difference to the average column density of the CGM.

#### 4. Emission measure

The absorption lines measure the column density of gas  $N_H = \mu n_e R$ , where  $\mu$  is the mean molecular weight  $\approx 0.8$ ,  $n_e$  is the electron density and  $R$  is the path-length. The emission measure, on the other hand, is sensitive to the square of the number density of the gas ( $EM = n_e^2 R$ , assuming a constant density plasma). Therefore a combination of absorption and emission measurements naturally provides constraints on the density and the path-length of the absorbing/emitting plasma.

While the EM varies by an order of magnitude across the sky, the average is  $EM = 0.0030 \pm 0.0006 \text{ cm}^{-6} \text{ pc}$ , assuming solar metallicity (Henley et al. 2010 and Yoshino et al. 2009; see discussion on EM in Gupta et al. 2010). Bregman et al. (2007) used  $EM = 0.009 \text{ cm}^{-6} \text{ pc}$  for solar metallicity which is a factor of three larger than the updated value used by Gupta et al. This would result in a factor of three higher density and a factor of three lower path-length compared to Gupta et al. (2012). Fang et al. (2006) used  $EM = 0.0047 \text{ cm}^{-6} \text{ pc}$ ; this would again yield proportionately higher density and lower path-length.

#### 5. Density and path-length of the warm-hot CGM

Combining the average  $EM = 0.003(\frac{Z_\odot}{Z})(\frac{8.51 \times 10^{-4}}{(A_O/A_H)})$  with the average absorption line column density, we can determine the density and the path-length of the absorbing gas. Reproducing equations 1 and 2 of Gupta et al, we have:

$$n_e = (2.0 \pm 0.6 \times 10^{-4}) \left( \frac{0.5}{f_{O\text{VII}}} \right)^{-1} \text{ cm}^{-3} \quad (1)$$

and the path length:

$$R = (71.8 \pm 30.2) \left( \frac{8.51 \times 10^{-4}}{(A_O/A_H)} \right) \left( \frac{0.5}{f_{OVII}} \right)^2 \left( \frac{Z_\odot}{Z} \right) \text{kpc} \quad (2)$$

where the Solar Oxygen abundance of  $A_O/A_H = 8.51 \times 10^{-4}$  is from Anders & Grevesse (1989),  $f_{OVII}$  is the ionization fraction of O VII and  $Z$  is the metallicity. For the observed temperature of about  $\gtrsim 10^6$  K, it is reasonable to expect  $f = 0.5$  (see, e.g., figure 4 in Mathur et al. 2003). As justified in Gupta et al,  $Z = 0.3Z_\odot$  is a reasonable assumption. For this metallicity the path-length becomes as large as  $R = 239 \pm 100$  kpc. As noted above, the density is independent of metallicity.

Bregman et al. have used  $A_O/A_H = 5.5 \times 10^{-4}$  and their quoted value of the path-length, 19 kpc, is for the Solar metallicity, which is highly unlikely in the CGM. These differences, together with column density differences, lead to a factor of 4.6 lower path-length. Fang et al. have used  $f_{OVII} = 1$  in their quoted value for the density and solar metallicity for the quoted path-length. Rasmussen et al. (2003), using  $Z = 0.3Z_\odot$  and  $A_O/A_H = 4.6 \times 10^{-4}$  find the scale length of the O VII absorber to be “at least 140 kpc”, significantly different from the Bregman et al. and Fang et al. results.

## 6. Sightline toward LMC-X3

The nearest neighbor of our Galaxy, the Large Magellanic Cloud (LMC) offers an unique opportunity to probe the CGM out to 50 kpc. Wang et al (2005) present *Chandra* LETG observations of LMC-X3; they detect absorption from O VII K $\alpha$  with  $\text{EW} = 20^{+14}_{-26}$  mA (90% confidence errors). The best-fit column density of about  $10^{16}$  cm $^{-2}$  is similar to what is observed along other sightlines. Does this suggest that the path-length of the CGM is as small as 50 kpc? Or is the absorption from the Galactic disk as suggested by Wang et al.?

There are several reasons why this may not be the case. First of all, the O VII EW is not well constrained; it is consistent with zero at  $2.7\sigma$ . Secondly, as noted by Wang et al., LMC-X3 is an X-ray binary and part of the O VII absorption may come from the outflow arising from the binary itself. The observed O VII column density must have contributions from the disk, the CGM and the binary, and the total itself can be significantly smaller than the best-fit value. Thirdly, there is a more than factor of two uncertainty in column density measurements toward LMC-X3, so for a constant density profile (discussed further below) the CGM path-length may well be a over factor of two higher, over hundred kpc. For these reasons, the LMC-X3 sightline does not offer additional significant insight into our understanding of the CGM. Moreover, the LMC sightline is indeed unique, so many other sightlines through the halo are needed to obtain the average properties of the CGM.

## 7. Galactic disk contribution to the $z = 0$ absorption

Our sightlines toward extragalactic sources pass through the Galactic disk, but the resolution of gratings on *Chandra* and *XMM-Newton* is not good enough to separate out the disk and CGM components. In an effort to find out whether most, if not all of the  $z = 0$  absorption arises in the Galactic disk, Yao et al. (2008) compared an extragalactic (Mrk 421) and a Galactic (4U 1957 + 11) sightline. The 4U source is located 10–25 kpc away and 2–4 kpc below the plane, sampling most of the Galactic disk in the vertical direction as well. On the other hand Mrk 421 sightline goes through the disk and the halo. Therefore the column density difference between the two gives an estimate of the halo contribution.

Yao et al. find column density in the 4U direction to be  $3.1_{-1.3}^{+5.1} \times 10^{15} \text{ cm}^{-2}$  and in the Mrk 421 direction to be  $10_{-3.4}^{+4.7} \times 10^{15} \text{ cm}^{-2}$ . Therefore the halo contribution is *at least*  $10 - 3 = 7 \times 10^{15} \text{ cm}^{-2}$ . This is the minimum because the column in the 4U direction is more through plane of the disk than in the vertical direction. If the disk is of uniform density on these scales, then the contribution from the vertical direction is about a fifth, or  $= 3/5 \times 10^{15} = 0.6 \times 10^{15} \text{ cm}^{-2}$ . This leads to the difference of  $9.4 \times 10^{15} \text{ cm}^{-2}$ , which is the halo contribution. This is a simple, straightforward logic and shows that most of the  $z = 0$  column density toward Mrk 421 is from the halo, not from the disk.

What Yao et al. write, however, is that they have an upper limit of  $4.8 \times 10^{15} \text{ cm}^{-2}$  for the halo contribution. How do they get this? They simultaneously fit the two spectra to get new values of column densities. This gives them the column in 4U direction to be  $7 \times 10^{15} \text{ cm}^{-2}$  with 90% upper limit of  $12.7 \times 10^{15} \text{ cm}^{-2}$ . Therefore they claim that the bulk of the column in the Mrk 421 sightline is accounted for, giving the upper limit quoted above. [Similar analysis is also done with another extragalactic source with similar results]. Why does the joint fitting give different result than the simple calculation mentioned above? The assumption in the joint fit is that the gas in the disk and the halo has the same temperature and velocity dispersion, but this assumption is unsupported. Moreover, their own analysis shows that this assumption is invalid; they find the b-parameter in the 4U line to be 155 km/s, while in the Mrk 421 line it is 64 km/s, therefore the two spectra should not be fit together. Secondly, the new column toward 4U they find is *more* than the 90% upper limit on this column from the 4U spectrum alone. This cannot be right and is most likely the result of a much lower b-value ( $= 70 \text{ km/s}$ ) in the joint fit than in the 4U spectrum alone; for the observed EW, a lower b-value would give higher column density. This brings out the folly in the analysis technique of joint fitting of unrelated spectra.

## 8. Discussion

Several authors have studied the  $z = 0$  absorption lines observed with *Chandra* and *XMM-Newton* gratings. They all agree that these lines are present and the line EWs presented in different papers are consistent with each other. There are, however, major differences in the final results and I have outlined some main reasons above. They are: (1) inferred column densities are different if saturation is not taken into account; (2) adopted values of the average emission measure are different; (3) adopted values of metallicity and oxygen abundance differ. Each of these differ only by factors of few, but together make orders of magnitude difference in the inferred mass. Since the volume goes as  $R^3$ , the mass is far more sensitive to the measured path-length than the density.

Gupta et al. (2012) have taken into account line saturation, used the most recent value for the average emission measure, adopted reasonable values for oxygen abundance and metallicity and concluded that the CGM in the warm-hot gaseous phase has low density (about  $2 \times 10^{-4} \text{ cm}^{-3}$ ) and the path-length is over 138 kpc( $1\sigma$ ). The inferred electron column density is then  $8.3 \times 10^{19} \text{ cm}^{-2}$  out to this distance, and  $= 3.0 \times 10^{19} \text{ cm}^{-2}$  out to 50 kpc. This is well within  $5.1 \times 10^{19} \text{ cm}^{-2}$  inferred from the pulsar dispersion measure using pulsars in LMC and SMC (Taylor & Cordes 1993). The inferred mass of this phase of the CGM is huge, over ten billion solar masses, comparable to the baryonic mass of the Galactic disk and significantly more than that in any other component of the CGM. There are, however, large uncertainties in all these estimates and they are presented explicitly in Gupta et al. (2012). In that paper we have also discussed all the assumptions and biases clearly and have shown that the results are fully consistent with theoretical models.

### 8.1. Assumption of constant density

In most papers discussed above, density of the CGM is assumed to be constant. While we have discussed this caveat in Gupta et al., it merits additional discussion. If the density is not constant, most likely it follows a profile such as a  $\beta$ -model, often observed in groups and clusters of galaxies. In this case, the emission measure would be sensitive to denser parts of the CGM and affect the density and path-length estimates. In this case, the inferred path-length would in fact be larger, and so the inferred mass. As noted above, the mass estimate depends critically on the inferred path-length.

Secondly, the assumption of a constant density is not as bad as it may look. In the simulations of Feldmann et al. (2012), the density is roughly constant above the Galactic disk out to about 100 kpc. Fang et al. (2012) also show that the hot gaseous halo of the

Milky Way is likely to have a low density extended profile as in Maller & Bullock (2004). Their inferred parameters are very similar to what we find in Gupta et al. Fang et al. also note that most of the missing baryons of the Galaxy can be in the warm-hot phase.

Thirdly, observations of other galaxies support the presence of extended low density halo, discussed further below.

## 8.2. Other galaxies

If such a large mass of warm-hot gas exists around our Galaxy, it should also be present around other similar galaxies. Indeed, emission from warm-hot gas has been detected around UGC 12591 out to 110 kpc (Dai et al. 2011) and around NGC 1961 out to 50 kpc. These authors calculate halo masses out to their virial radii which are 3–6 times smaller than the MW halo, once adjusted for the gravitational mass. First of all, this factor is well within the uncertainties of all measurements. Secondly, small differences in the parameters of a beta-model can easily make a large difference when extrapolated to large radii. Thirdly, galaxy mass many not be the relevant parameter for the gaseous halo mass; Tumlinson et al. (2011) have shown that the specific star formation rate of a galaxy is more important instead. Thus, observations of other galaxies are not inconsistent with the results for our Galaxy.

Recently Williams et al. (2012) investigated intervening X-ray absorption line systems toward H2356 – 309 observed by Buote et al. (2009), Fang et al. (2010) and Zappacosta et al. (2010). They found that three of the four absorption systems originate within virial radii of nearby galaxies or groups with projected distances of 100s of kpc. These observations give additional evidence for extended warm-hot halo around other galaxies. The  $z = 0.030$  system in Williams et al. is particularly relevant for the present discussion because the observed sightline passes through the halo of a nearby galaxy. The observed column density of this absorption system is  $\log N_{O\text{VII}} = 16.8^{+1.3}_{-0.9}$  at an impact parameter of  $D = 90$  kpc from a nearby galaxy with virial radius of  $R = 160$  kpc. The path-length of the absorber is then  $2\sqrt{R^2 - D^2} = 264.6$  kpc. From the path-length and the column density we calculate the density  $= 7.4 \times 10^{-4} \text{ cm}^{-3}$  (for O VII ionization fraction and metallicity as in Gupta et al. 2012). This shows that such a high density, even more than what we calculated for the MW halo, is present out to about a hundred kpc from another galaxy as well. This not only shows a MW-type halo around another galaxy, it also shows that the assumption of a flat density profile is reasonable.

### 8.3. Future progress

All the papers to date have used an average emission measure for the halo; ideally we need emission measures close to the absorption sightlines. Observations with *XMM-Newton* and *Suzaku* would be particularly useful in this regard. High sensitivity observations discriminating among different halo density profiles will be a step forward from the constant density model. Higher S/N spectra of many sightlines will place better constraints on the column density. Thus newer and better data and better modeling will place tighter constraints on the physical parameters of the CGM.

There is room for progress on theory side as well. We have noted in Gupta et al. that the observational results are consistent with recent theoretical models. As we were about to post this article, another theory paper on the CGM of Milky Way appeared on the arXiv by Fang, Bullock & Boylan-Kolchin (2012). Their results for extended hot gas halo profiles are again consistent with Gupta et al. and they discuss future avenues for extending their theoretical work.

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